A PARAMETERIZED INVERSION MODEL FOR SOIL MOISTURE AND BIOMASS FROM POLARIMETRIC BACKSCATTERING COEFFICIENTS

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ABSTRACT

A semi-empirical algorithm for the retrieval of soil moisture, root mean square (RMS) height and biomass from polarimetric SAR data is explained and analyzed in this paper. The algorithm is a simplification of the distorted Born model. It takes into account the physical scattering phenomenon and has three major components: volume, double-bounce and surface. This simplified model uses the three backscattering coefficients (σ_{HH}, σ_{HV} and σ_{VV}) at low-frequency (P-band). The inversion process uses the Levenberg-Marquardt non-linear least-squares method to estimate the structural parameters. The estimation process is entirely explained in this paper, from initialization of the unknowns to retrievals. A sensitivity analysis is also done where the initial values in the inversion process are varying randomly. The results show that the inversion process is not really sensitive to initial values and a major part of the retrievals has a root-mean-square error lower than 5% for soil moisture, 24 Mg/ha for biomass and 0.49 cm for roughness, considering a soil moisture of 40%, roughness equal to 3cm and biomass varying from 0 to 500 Mg/ha with a mean of 161 Mg/ha.

***Index Terms*—** Soil moisture, roughness, biomass, polarimetry

1. INTRODUCTION

Soil moisture is a key parameter in the global warming context being part of water, energy and carbon cycles. Over bare surfaces, the soil moisture retrieval from polarimetric backscattering coefficients has been shown possible using some empirical [1-3] or physical models such as the Small Perturbation Model (SPM) [4]. However for vegetated-covered surfaces, soil moisture estimate is a big challenge since the vegetation canopy is a complex environment where several scattering mechanisms make the problem more difficult. Moghaddam et al. developed an algorithm to estimate soil moisture under a boreal forest using L- and P-band SAR data [5]. For their studied area, double-bounce between trunks and ground appears to be the most important scattering mechanism. Thereby, they implemented parametric models of radar backscatter for double-bounce using simulations of a numerical forest scattering model. Then a non-linear optimization process estimated the dielectric constant. Hajnsek et al. showed the potential of estimating the soil moisture under agricultural vegetation using L-band polarimetric SAR data [6]. They used polarimetric-decomposition techniques to remove the vegetation layer effect then to estimate soil moisture of the underlying ground.

The Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) system of NASA/JPL will provide high-resolution observations of soil moisture over nine representative regions of North America and quantify the soil moisture variation on carbon fluxes estimate. The AirMOSS system is a dual-polarimetric synthetic aperture radar that will operate in P-band. The goal of this paper is to present a parameterized inversion model for soil moisture, biomass and roughness using the three backscattering coefficients: σ_{HH}, σ_{HV} and σ_{VV} and based on physical parameters. This semi-empirical model is a simplification of the distorted Born model [7-8]. Volume backscattering comes from crown and trunk, double-bounce arises from interactions between either crown and ground or trunk and ground, and surface scattering is directly scattered by the soil surface with some attenuation through vegetation. First of all, the model formulation is presented. Next, the estimation process based on a non-linear optimization method is explained. Finally a sensitivity analysis based on some simulated data is done to assess the accuracy of the inversion process in function of initial values.

2. THE MODEL

The total backscattering coefficient measured by SAR is in general represented by:

$$\sigma^0_{pq} = \sigma^0_{pqV} + \sigma^0_{pqDB} + \sigma^0_{pqS}$$

where p and q stands for the polarizations of the received and transmitted radar signals and V, DB and S are volume, double-bounce and surface scattering mechanisms. Each scattering mechanism has simplified expressions taking into account the average volume attenuation, a trunk-ground interaction assuming the tree trunks are vertically distributed and the Fresnel reflectivity of surface. This forward model (CM) is based on simplifications of a two-layer forest model to separate structural and dielectric parameters [7-8]. The structure of the forest is contained in the above ground biomass (W). The soil moisture information is in the double-bounce term with the Fresnel reflectivity and in the bare soil scattering. Physical phenomena are gathered in these terms taking into account the attenuation through the vegetation. A set of structural forest variables is used to parameterize the forward model. Then to anticipate some calibration issues and some errors in the forward model, some factors are fitted with ground measurements assuming the soil moisture equal to 40 $cm^3.cm^{-3}$, a roughness of 3 cm and an incidence angle of 45º. The model predictions for the three backscattering coefficients versus the biomass for La Selva forest are shown on Fig.1 below.

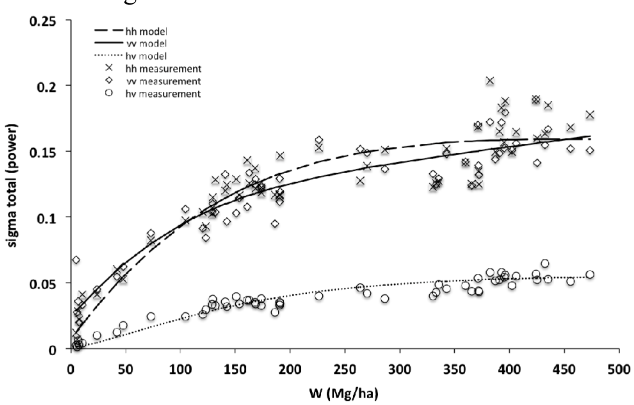

Fig. 1:Backscattering coefficients (in power) - σ_{HH}, σ_{VV} and σ_{HV} using AirSAR P-band data over La Selva. Crosses are the ground measurements for σ_{HH}, diamonds for σ_{VV} and circles for σ_{HV}. Dashed line is the model prediction for σ_{HH}, continuous line is for σ_{VV} and dotted line is for σ_{HV}.

The root-mean-square errors and the correlation coefficient between estimates using the model and ground measurements for the three backscattering coefficients (σ_{HH}, σ_{HV} and σ_{VV}) are listed in Table 1. They show a very good agreement between model predictions and in-situ data.

	HH	VV	HV
RMSE	0.016819935	0.0142891	0.005095341
R^2	0.930469068	0.933139812	0.954046418

Table1: RMSE and correlations coefficient computed between model and ground measurements.

3. ESTIMATION PROCESS

3.1. Initialization

The procedure uses a Levenberg-Marquardt non-linear least-squares method to estimate the structural parameters which are the biomass, the dielectric constant and the roughness. To compute the soil moisture from the dielectric constant, the semi-empirical model of Hallikainen et al. [9] is used. The first step of this process is to give a "first guess" to initialize the three unknowns parameters. To do that bare surfaces are differentiated from vegetated areas so soil moisture and roughness algorithms such as Oh et al. [1], Dubois et al. [2], Shi et al. [3] or SPM [4] can be used to initialize the pixels identified as bare surfaces. Later we explain how to initialize the vegetated areas. A segmentation of non-forested and forested areas is first done using backscattering coefficients and NLCD data as well. The NLCD data is used to identify water bodies and developed areas which are masked out by allocating the *NaN* value. Once bare surfaces are selected the empirical model of Oh et al. [1] is used to estimate soil moisture and roughness. Then, the mean value of bare surfaces is computed over the entire SAR image and is allocated to every vegetated pixels. Concerning biomass a simple fit (SM) of the form:

$$\sqrt{W} = a_0 + a_1\sigma_{HH} + a_2\sigma_{HV} + a_3\sigma_{VV}$$

is computed using ground measurements. This equation is then applied to the entire SAR image to get a biomass map. Initialization is now done for the three parameters and the inversion process can be run.

3.2. Inversion

The procedure uses the Levenberg-Marquardt non-linear least-squares method to estimate the structural parameters: biomass, dielectric constant and roughness. The Levenberg-Marquardt is a local optimization process defined here by:

$$S(W,\varepsilon,s) = \sum_{i=1}^{n}\left[\sigma_{pq_i} - f(\theta,W,\varepsilon,s)\right]^2$$

In our case, we run the optimization procedure over the entire SAR image pixel by pixel. In this case, σ_{pq} is the backscattering value recorded by the SAR system at this particular pixel, *f*() is the model equation, θ is the incidence angle at that pixel and W, ε and s are the parameters to be optimized for this pixel.

To avoid some meaningless values, some limits are set for the three parameters:
-$0 < 0.5\ \varepsilon_0 < \varepsilon' < 1.5\ \varepsilon_0 < 80$
-$0 < 0.8\ W_0 < W' < 1.2W_0 < 500$ Mg/ha
-$0 < 0.8\ s_0 < s' < 1.2\ s_0 < 20$ cm
Where ε' and ε_0 are the estimated and initial dielectric constants respectively. W' and W_0 are the estimated and initial biomass values respectively. S' and s_0 are the

estimated and initial roughness values respectively. Next, when soil moisture (or roughness or biomass) exceeds a threshold then the value of the soil moisture (or roughness or biomass) at that pixel is replaced by the 3x3 average soil moisture (or roughness or biomass) of surrounding pixels.

4. SENSITIVITY ANALYSIS

The sensitivity of this model is tested by running 1000 different tests where the initial value of each parameter varies randomly. From La Selva SAR data (σ_{HH}, σ_{VV}, σ_{HV}) acquired by AirSAR in 1994 a biomass map is computed using SM. Soil moisture and roughness are set to a single value (m_v=40% and s=3 cm). The three parameters are inserted in CM to get some simulated backscattering images (σ_{HH_bis}, σ_{VV_bis}, σ_{HV_bis}). The ensuing simulated backscattering images are then re-inserted in the inverse model (CM^{-1}) to get biomass (W'), soil moisture (m_v') and roughness (s') estimates. The initial values for the three parameters are set randomly such as for biomass W_0=W+m with m $\in$ [-100; +100] Mg/ha, m_{v0}=m_v+k with k $\in$ [-0.5m_v; 0.5m_v] and s_0=s+l with l $\in$[-s; +s]. This test has been run 1000 times. Finally the estimated parameters are compared to the initial ones (W'/W, m_v'/m_v, s'/s). The steps of this process are summarized in the diagram below.

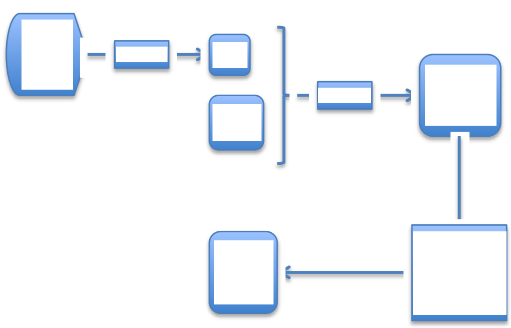

Fig.2: Diagram showing the steps of the sensitivity analysis

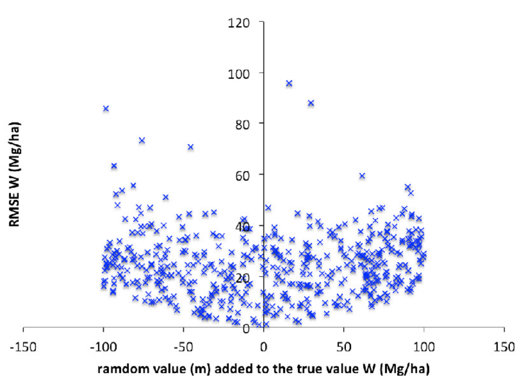

Fig. 3: biomass RMSE (Mg/ha) in function of the random value added to the true value (m)

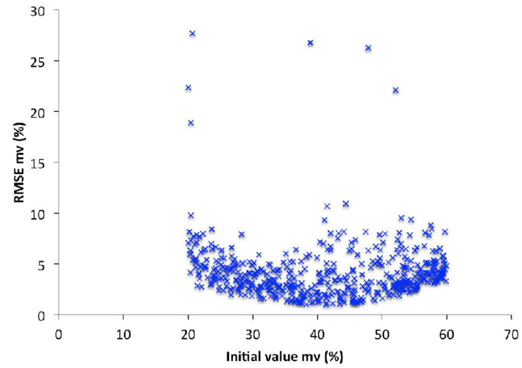

Fig. 4: soil moisture RMSE (%) in function of the initial value (m_{v0})

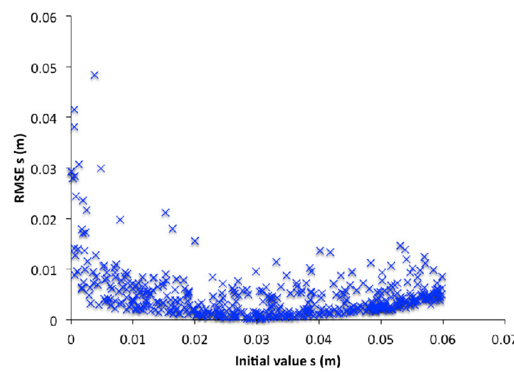

Fig. 5: roughness RMSE (m) in function of the initial value (s_0)

This analysis shows that the inversion is not really sensitive to the initial values. Figure 3 shows that the biomass root-mean-square error is lower than 40 Mg/ha in most cases. The mean value is equal to 24 Mg/ha. For soil moisture 73.9% of the tests have a RMSE lower than 5% and the mean is about 4%. Figure 5 shows that the roughness RMSE is lower than 1cm in most cases (91.4%) and the mean is about 0.4948 cm. When the results are not equal to the expected ones it is explained by the fact that the inversion is reaching another local minimum.

5. CONCLUSION

A semi-empirical model to retrieve soil moisture, biomass and roughness is presented and analyzed in this paper. This model is a simplification of the distorted Born model. The model needs to be parameterized with a set of structural parameters about the forest and some ground measurements. The predictions of the model agree quite closely with the ground measurements. The correlation coefficients between estimated backscattering coefficients and in-situ data are higher than 0.9 for σ_{HH}, σ_{VV} and σ_{HV}. This model is used to retrieve soil moisture, biomass and roughness by applying the Levenberg-Marquardt algorithm. The initialization of this technique consists of estimating soil moisture and roughness over bare surfaces then allocating the mean value of these bare surfaces to the forested areas. For biomass a simple regression is computed between ground measurements and backscattering coefficients that allows to construct a biomass map afterwards. The inversion process is then run and bounded to avoid some meaningless values. The sensitivity of this process in function of initial values is assessed and shows that the inversion is not really sensitive to initial guesses. The initial value is randomly picked up in the range ± 50% of the true value for soil moisture, ± 100% of the true value for roughness and ± 100 Mg/ha of the true value for biomass. Results have a RMSE lower than 5% for soil moisture, lower than 0.5 cm for roughness and lower than 40 Mg/ha for a major part of the tests.

6. REFERENCES

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7. ACKNOWLEDGMENT

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